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Carbon Accounting in Local-Scale Land Use and Land Cover Change

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Abstract

Complex land use and land cover change (LULCC) processes modify ecosystems' ability to store and sequester carbon and regulate the climate, resulting in thermally uncomfortable climates and even more carbon emissions in an unchecked cycle. The value of potential loss of such climate ecosystem services remains understudied in urbanization planning and development. Using ecosystem modeling, this research quantifies potential changes of carbon storage and sequestration for a case of future LULCC in a tropical country by building an initial baseline carbon account of the existing forest. This study looked at a unique case of planned local-scale LULCC in Singapore where a secondary forest, Punggol Forest, is slated for conversion into a mixed-use residential neighborhood, Punggol Eco-Town. Carbon accounting is conducted to determine the carbon footprint of the LULCC, specifically for carbon storage and rate of carbon sequestration, using a sampled tree inventory with primary data collection. The results suggest that considerations of urban tree species selection in urban forestry are important in planning in order to reduce climate ecosystem services loss as a result of development. It is also a first step in using urban forestry tools for carbon accounting in decision-making for urban planning.

Keywords: land use and land cover change (LULCC), carbon accounting, urban forestry, urban planning

Author's Note:
This research is an adapted version of my undergraduate honors thesis at the National University of Singapore, where I was advised by A/P Winston Chow. The original paper has an urban climatology focus that also considers microclimate change, as observed by components of the surface energy balance, and used a second model called Local-Urban Meteorological Parameterization Scheme (LUMPS) to generated projections for scenarios of urbanization. This component of carbon storage and sequestration was however the most fun, to me, of the entire process of primary data collection using forest sampling methods. I am fascinated by the application of this methodology in evidence-based decision-making for policy with quantitative values. I

believe that sustainable development in urbanization and urban planning must be accompanied with an awareness of ecosystem services that are lost, and further design to restore them in some way. While this paper takes a focused approach to modeling climate ecosystem services, the future must include integrated solutions for ecosystem services across definitions within the Millennium Ecosystem Assessment.

Introduction

Extensive, accelerated land use and land cover change (LULCC) has dramatically altered our physical environment with unprecedented impacts on ecosystem functioning (Lambin et al., 2001, Turner et al., 1990). The ability of to support the needs of the human enterprise, also known as ecosystem services, (Vitousek et al., 1997, Bonan, 2008) is lost during LULCC processes of deforestation and urbanization.

Carbon storage and sequestration are crucial ecosystem services in a warming world where carbon sinks and stores are depleting rapidly. Deforestation reduces the amount of carbon stored in forest biomass (Lal, 2005) and removes the carbon sequestration service provided by trees (Rowntree and Nowak, 1991). Quantifying the loss of ecosystem services in carbon sequestration and storage is hence important to city planners to design for mitigation against climate change.

LULCC poses a challenge for policymakers aiming to balance human population needs with long-term environmental sustainability. Although researchers have long called for change in the way ecosystems are managed to reduce detrimental impacts of LULCC, it is only until recently that ecosystem services and values are being considered in decision-making processes to inform urban planning and land management (Lambin and Geist, 2008).

Forests have positive effects on human well-being through ecosystem functions, one of which is carbon removal and storage from the atmosphere as climate change mitigation. One solution in urban areas to reducing the loss of carbon sequestration and storage is green infrastructure design, which incorporates vegetation into an urban matrix (Tyrväinen et al., 2005, Gill et al., 2007).

The change in carbon stored and sequestered can be quantified by an existing model that uses primary data to build a sample tree inventories of forests given relevant biological data inputs. This research brings quantitative modelling LULCC research into the scope of policy with a specific local case study of considering climate ecosystem services in urban planning. The temporal element of ecosystem service loss is captured as a baseline snapshot prior to planned, projected change as the study area undergoes deforestation and subsequent urbanisation.

This research generates values for carbon storage and sequestration loss for a specific future LULCC in Singapore based on official plans for land management. Singapore is a densely populated, highly urban city-state, with over 95% of the original vegetation cover cleared (Corlett, 1992). The government extensively allocates land uses within the limited space to plan for sustainable urban growth (Urban Redevelopment Authority, 2015a). This small-scale LULCC enables the possibility of carbon accounting, which can inform urban planning options to compensate for the accompanying ecosystem service loss.

Literature Review

Carbon storage and sequestration services modulate the climate through biogeochemical regulation (West et al., 2011). Both are provided by carbon stocks, the carbon-carrying capacity of vegetative biomass and soil. Forest ecosystems *sequester* carbon through photosynthesis and net growth, *storing* it as biomass. If carbon uptake exceeds the amount released through decay, respiration or burning, a forest is regarded as a 'sink', and the sum of carbon stocks increases (Apps, 2003). Globally, forests remove approximately 2.6Gt of atmospheric carbon dioxide (CO_2) annually (Vogt et al., 2006).

Deforestation and forest degradation, primarily of tropical forests, are the next most important contributors to climate change after fossil fuel use. During deforestation, above-ground carbon in vegetation and soil are lost as biomass is removed (Lal, 2005), releasing existing carbon stocks and losing the carbon sequestration service that offsets CO_2. LULCC-related CO_2 emissions are attributed to deforestation by fires, timber exploitation and intensive cultivation of cropland soils (Le Quéré et al., 2009). These were previously known to account for up to 20% of global carbon emissions (Houghton, 2005), a number revised to 12% recently (Canadell et al., 2007; Van der Werf et al., 2009). No longitudinal data on the contribution of carbon emissions from LULCC by land conversion from forest to specific land uses is available. Experts estimate that of the global urban expansion rate of 20,000 km^2/year, 10% of this expansion intrudes on forests (Holmgren, 2006). Global deforestation for urban land expansion is likely to accelerate, with forecasts estimating a possible 185% increase in urban land extent from 2000 (Seto et al., 2012). The relationship between carbon ecosystem services and LULCC at the local scale has been understudied due to complex urban dynamics; 'urbanisation' in the literature is defined as an expansion of both urban populations and areas (Heilig, 2012).

Climate change is an important issue for cities as both home to majority of the world's population and major carbon sources (Hoornweg et al., 2010). An advantage of city-scale analysis is that it coincides closely with administrative decision-making boundaries (Hunt and Watkiss, 2011). There is increasing attention on the need for cities to quantify and manage their carbon footprint at the local scale (Gurney et al., 2015). Urban forestry is one way to restore carbon storage and sequestration ecosystem services (Rowntree and Nowak, 1991) and offset carbon emissions. Forest management methods like reforestation and afforestation to reverse LULCC, increasing the carbon density of existing forests and reduction of deforestation and degradation are being explored (Canadell and Raupach, 2008).

Methodology

This case study is of LULCC in Singapore, specifically the northern part of Punggol Eco-Town, where land is undergoing conversion from secondary forest to urban mixed-use residential land. It is a prime illustration of local climate change as a result of loss of climate ecosystem services due to anticipated urban development in response to projected demographic change within a local planning context.

This study specifically focuses on an area of land occupied by Punggol Forest. At present, it consists of secondary regrowth forest on abandoned coconut, rubber and fruit plantation land and small patches of mangroves. This 2.14km^2 area will be clear cut and deforested to make way for part of Punggol Eco-Town.

Carbon accounting in this study is done with primary data collection followed by the i-Tree Eco software suite by the United States Department of Agriculture Forest Service as a modelling tool. A sample inventory of trees in plots within the study area forest is used as input data to accurately estimate urban forest structure, total carbon stored and net carbon annually sequestered. Plot sampling was performed by a trained crew managed by the lead investigator who was present for all fieldwork sessions. Pair review was conducted to ensure quality control. Fieldwork took place over the course of seven days in early June 2015.

Figure 1 Photograph showing lack of access due to construction work, taken at 1°25'52"N, 103°54'24"E

Source: Author's own

The study site of was first assessed for accessibility as an important limitation on the surveyable area since the survey had to be conducted on foot in a high density tropical forest with tall grasses. As construction and deforestation was already under way, access was restricted by construction fences (Figure 1). Through site visits, it was ascertained that a 303,251m^2 area (shaded red in Figure 2) could not be accessed within the study site. It was thus omitted from the vegetation survey area.

Figure 2 Vegetation survey plots mapped out across stratified study site.

Source: Google Earth (updated 24 July 2015)

A proportionate stratified accessibility sampling method was used in plot selection. The accessible area of Punggol Forest was divided into two strata by ground cover characteristics, forest (Figure 3) or grass cover (Figure 4), based on Google Earth satellite image observations for tree cover density. Twenty non-overlapping plots were selected from either stratum based on proportion of area (see Table 2). Plots were preferentially but systematically selected to spread out across the study site with each plot at least 25m away from another. The bias in plot selection is influenced by access due to criteria for fieldwork crew safety and sampling feasibility, important considerations for fieldwork (Woodward et al., 2009). Plots sampled were limited to accessible regions and slopes lower than 35°. Dangerous crossings over man-made or natural waterbodies such as streams, wells and deep drains and other potential hazards such as wild dogs were avoided. Thus, plots sampled were spatially biased towards the more southerly part of Punggol Forest. The location of all twenty plots can be seen in Figure 10.

Table 1: Study site according to ground cover characteristics.

Ground cover type	*Area (m^2)*	*Proportion of Area*	*Number of Plots Sampled*
Forest cover	1,108,792	0.771	16
Grass cover	327,918	0.228	4
Total extent	1,436,710	1	20

The standard error of this sampling method is approximately 35% as determined by a prior study on urban forests (Nowak et al., 2008b). However, this is an estimate as Punggol Forest is smaller in size compared to the urban forests in the United States of that study. Thus, together with practical constraints, the selection of twenty sample plots is justified and acceptable for this study.

Figure 3 Photograph of a vegetation survey sample plot classified as 'forest cover'

Source: Author's own

Figure 4 Photograph of a vegetation survey sample plot classified as 'grass cover'

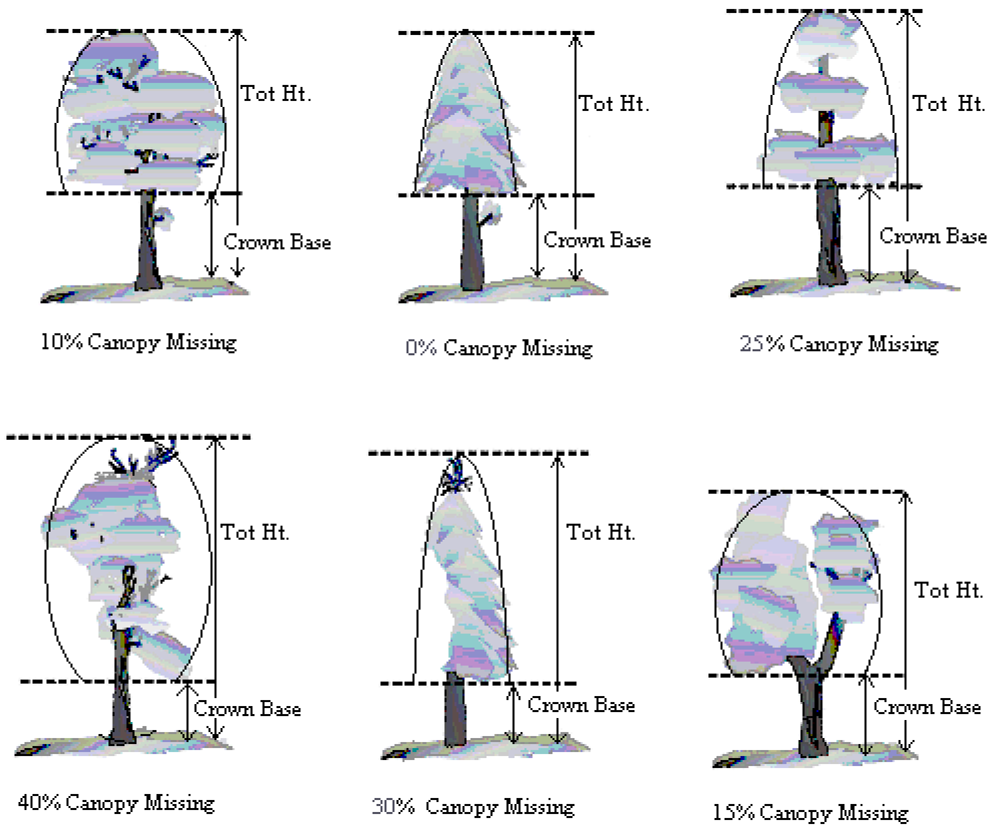
Source: Author's own

Each concentric 0.1acre plot with an 11.3m radius was assessed in a full vegetation cover survey. A Garmin eTrex 20x Global Positioning System (GPS) unit was used to collect location and directional data oriented around a reference object, usually a tree, in the centre of each plot. Other forestry equipment used include transect tapes, diameter at breast height (DBH) tapes and Haglöf ECII electronic clinometers.

Plot characteristics recorded include tree cover, shrub cover and land use. Ground cover was measured in terms of percentage of natural materials such as rock, bare soil, mulch, herbs, grass (maintained and unmaintained) and water, and urban materials including building, cement and tar. The herbaceous layer, consisting of non-woody stems, were considered as part of ground cover (i-Tree, 2010). Shrubs and saplings, defined as woody material with DBH at 1.37cm of less than 5cm, were excluded. The Delphi method was used to aggregate the values estimated by the fieldwork crew in midpoints of 5% intervals (MacMillan and Marshall, 2006).

Trees were defined based on DBH of at least 5cm, a threshold selected over the i-Tree Eco's value of 2.54cm to reduce misidentification of young trees. As a result, the extrapolation of plots in running i-Tree Eco would produce a conservative estimation. For this vegetation survey, palms were included in this category.

Figure 1 Illustration of percentage canopy missing and tree height measurements



Source: i-Tree Eco v5.1.7. (n.d.)

Several tree characteristics on tree condition were also collected. Tree height was measured using a clinometer for the height of the tree to live top, height to crown base and total tree height. Crown width in the north-south and east-west directions were measured using transect tape. The percent of the crown volume that is missing was estimated in terms of percentage of foliage absent due to dieback, defoliation and uneven crowns, though this was at times difficult for tall trees in the densely intersecting canopy (see Figure 5). Crown light exposure, the number of sides (including the top) of the tree receiving sunlight, was encoded as a value from 0 to 5 according to i-Tree Eco protocol. For trees lying on their side, leaning or situated on sloping ground, an aboveground reference point was taken according to i-Tree Eco protocol.

Trees not identified during fieldwork were later identified with the assistance of a botanist from the Department of Biological Sciences at the National University of Singapore using leaf samples and photographs. Out of the 24 species of trees that were identified (Appendix A), four were not found within the i-Tree Eco Species Code List inventory list, and were thus replaced with proxy species based on similar characteristics of leaf shape, leaf size, approximate range of tree height and crown shape (see Appendix B).

All vegetation survey data were entered manually into i-Tree Eco using the mobile data collection system. This international project on the forest inventory of Punggol Forest was processed by researchers at the United States Forest Service. No additional input data on runoff or pollutant values were included due to the lack of available information on Singapore. Thus, outputs excluded bioemissions and rainfall interception data. Although i-Tree Eco is parameterised primarily for temperate urban forests, errors are minimised by using species or genus-specific values (i-Tree Eco v5.1.7., n.d.).

i-Tree Eco estimates the forest structure and characteristics of vegetation, through the use of species-specific regression equations in converting empirical leaf-area estimates into leaf biomass, and subsequently scales it according to tree condition ratings. The values are further scaled proportionally by a crown competition factor to account for shading by overlapping tree crowns. Species diversity indices and species richness are also calculated (Nowak et al., 2008a).

i-Tree Eco also estimates the carbon storage value as biomass through species-specific allometric equations derived from the literature (Nowak and Crane, 2002, Nowak, 1994), and if unavailable, an average of equations from the same genus, failing which broadleaf equations are used (Nowak et al., 2008a). Aboveground biomass is converted to tree biomass assuming a globally averaged root-to-shoot ratio of 0.26, a slight overestimation compared to the tropical ratio of 0.24 (Cairns et al., 1997), that may affect this study. Fresh weight biomass equations are adjusted to dry weight with species-specific equations from the literature (Nowak and Crane, 2002). Only wood biomass is considered for deciduous trees due to the annual shedding of leaves. The total dry weight biomass of trees is converted to total stored carbon by a factor of 0.5 (Chow and Rolfe, 1989).

i-Tree Eco estimates carbon sequestration rates based on DBH and height growth rates year-round. Individual tree growth is controlled by the estimated growing degree days, an accumulative value localised by latitude and related to collected crown light exposure values. These values are adjusted based on tree condition inferred from crown dieback data. Carbon emissions from decomposition were calculated by combining the probability of tree death within the next year for live trees and the rate of natural decomposition of 20 years for existing dead trees (i-Tree, 2010). Thus, the calculated net carbon sequestration annual rate is the carbon storage difference between one year and the next, as aggregated by mortality probability, decomposition and growth.

Results

Tree inventory of Punggol Forest

This tree inventory of Punggol Forest is a snapshot of current conditions in the study site prior to LULCC transformation. This establishes a baseline for anticipated changes to ecosystem services in terms of carbon storage and sequestration due to future deforestation.

i-Tree Eco reports 47,957 trees within the 1.43km^2 accessible region of Punggol Forest at a density of 33,380 per km^2. Of the 27 species, the most abundant is *Caryota mitis*, or fishtail palm (17.6%), followed by the *Delonix regia*, commonly known as the Flame of the Forest (15.7%). The majority of trees (42.3%) have a DBH of between 7.7 and 15.2cm.

In terms of biodiversity value, Punggol Forest has low species richness of 10.93 (Simpson's Reciprocal Index) and low species evenness at 0.8172. By extrapolating the average of the 0.04046-hectare sampled plots according to equation (1), the approximate number of species per hectare is 33.75 per hectare.

$$\sum_{i=1}^{n} \frac{\frac{X_i}{0.04046}}{n} = 33.75\ species/ha \qquad (1)$$

where X_i = no. of species in plot i
n = no. of plots = 20

The diversity of Punggol Forest is high for a secondary regrowth forest, with a Shannon-Weiner index value of 2.69, compared to other regenerated sites in Singapore (Shono et al., 2006).

The most dominant tree species found in Punggol Forest, based on number of individuals (percent population), relative frequency, density and basal area (importance value) and tree cover (percent leaf area) are shown in Table 2.

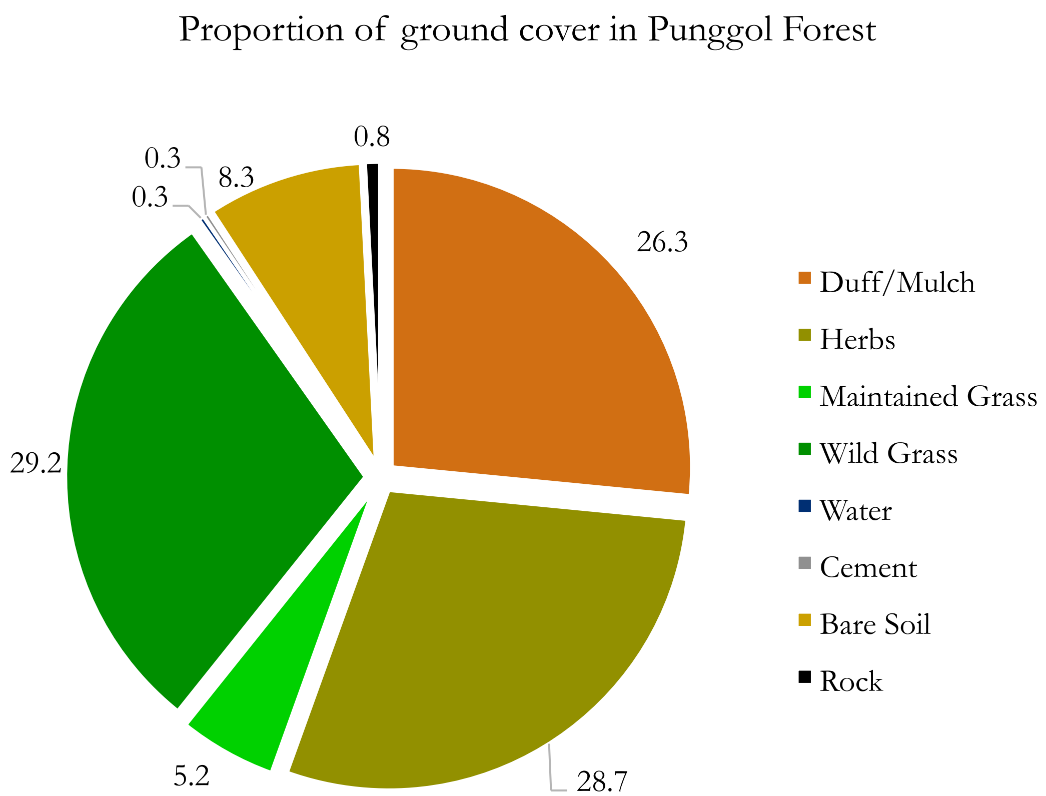
Table 2 Tree Species Diversity

SPECIES (REPLACED)	PERCENT POPULATION	IMPORTANCE VALUE	PERCENT LEAF AREA
Delonix regia	15.7303	51.5182	35.7879
Caryota mitis	17.6027	28.4278	10.8251
Casuarina equisetifolia	8.9891	28.2086	19.2195
Sapindus spp. *(Nephelium lappaceum)*	11.9854	16.2809	4.2955
Syzygium spp.	3.7448	10.0838	6.339
Artocarpus heterophyllus (Durio zibenthinus)	2.9964	8.6383	5.6419
Claoxylon indicum	4.1203	8.5707	4.4504
Cinnamomum iners	5.243	6.6014	1.3584
Toona spp. *(Aphanamixis polystachya)*	4.8688	6.0365	1.1677
Terminalia catappa	2.2467	5.3328	3.0861
Syzygium grande	3.3706	4.5264	1.1558
Maprounea guianensis (Heavea brasilensis)	4.1203	4.5075	0.3873
Pipturus argentus	3.7448	3.9414	0.1966
Leucaena leucocephala	2.6221	2.9796	0.3575
Macaranga gigantea	0.7485	2.3213	1.5728
Garcinia hombroniana	1.1239	2.1725	1.0486
Eucommia ulmoides	1.1239	1.7793	0.6553
Pterocarpus indicus	1.1239	1.4814	0.3575
Acacia auriculiformis	1.1239	1.3086	0.1847
Roystonea spp.	0.7485	0.9868	0.2383
Albizia saman	0.3742	0.9819	0.6077
Gordonia spp.	0.3742	0.9224	0.5481
Bambusa multiplex	0.3742	0.833	0.4587
Terminalia brassii	0.3742	0.416	0.0417
Manihot spp.	0.3742	0.3921	0.0179
Dillenia suffruticosa	0.3742	0.3742	0
Andira inermis	0.3742	0.3742	0

Source: i-Tree Eco

While shrubs are excluded from this study, the ground cover of Punggol Forest is shown in Figure 6.

Figure 6 Modeled Ground Cover of Punggol Forest



Carbon Storage and Sequestration

i-Tree Eco reports the annual rate of carbon sequestration in Punggol Forest to be 1637kg/year/ha. The carbon storage per area is 74421kg/hectare, which means a potential release of 18708mt of carbon into the atmosphere during deforestation. The forest provides an annual net carbon sequestration value of 262.5mt/year (Table 3) and oxygen production at a rate of 2785kg/year/ha, or 400mt/year in total.

Table 3 Carbon Sequestration Values from i-Tree Eco

SPECIES (REPLACED)	CARBON (MT)		GROSS SEQ (MT/YR)		NET SEQ (MT/YR)	
	VALUE	SE	VALUE	SE	VALUE	SE
TOTAL	18708.83	5663.84	411.44	79.93	262.5	91.79
Delonix regia	8889.68	4601.65	120.14	41.13	83.06	36.99
Syzygium spp.	1996.95	1693.08	41.01	32.27	34.98	28.53
Artocarpus heterophyllus (Durio zibenthinus)	1934.17	1225.1	48.67	29.4	44.3	26.65
Casuarina equisetifolia	1169.04	686.97	29.79	18.1	26.93	16.57
Sapindus spp. (Nephelium lappaceum)	1048.58	699.16	40.24	28.82	29.03	29.38
Cinnamomum iners	1022.8	1018.53	35.13	34.59	31.95	31.42
Terminalia catappa	540.59	452.82	5.2	2.81	-68.99	74.18
Macaranga gigantea	428.05	407.46	10.44	9.08	9.47	8.17
Toona spp. (Aphanamixis polystachya)	335.93	335.39	15.77	15.74	13.84	13.82
Caryota mitis	283.19	144.22	2.8	1.34	2	0.92
Syzygium grande	210.05	166.14	10.52	7.95	9.89	7.43
Gordonia spp.	128.18	127.98	4.54	4.54	4.25	4.24
Pterocarpus indicus	103.75	103.58	6.2	6.19	5.95	5.94
Claoxylon indicum	103.51	103.35	8.37	8.36	8.12	8.11
Garcinia hombroniana	102.25	102.09	5.72	5.71	5.48	5.47
Maprounea guianensis (Heavea brasilensis)	96.45	96.3	6.87	6.86	6.35	6.34
Albizia saman	96.12	95.97	3.83	3.83	3.61	3.61
Eucommia ulmoides	91.42	91.28	5.02	5.01	4.81	4.8
Pipturus argentus	56.18	56.09	4.88	4.87	1.77	1.77
Acacia auriculiformis	35.59	31.23	2.69	1.94	2.6	1.87
Leucaena leucocephala	11.84	11.82	1.72	1.72	1.26	1.26
Bambusa multiplex	8.39	8.38	0.07	0.06	0.04	0.04
Terminalia brassii	6.26	6.25	0.78	0.77	0.76	0.76
Roystonea spp.	5.72	5.71	0.08	0.08	0.06	0.06
Dillenia suffruticosa	1.76	1.76	0.38	0.38	0.37	0.37
Manihot spp.	1.39	1.39	0.33	0.33	0.33	0.33
Andira inermis	0.97	0.97	0.27	0.27	0.27	0.27

Source: i-Tree Eco

Figures 7 and 8 show the gross and net annual carbon sequestration rates by each tree species, with a clear positive carbon sequestration rate by almost all species, led by *Delonix regia*, *Artocarpus heterophyllus* (replacing *Durio zibenthinus*) and *Syzygium* species. In contrast, the *Terminalia cattappa* species has negative net sequestration, indicating an annual rate of carbon release into the environment. This is due to the preponderance of dead *Terminalia cattappa* trees found within Punggol Forest, which release carbon as they decompose, and the higher likelihood of mortality for this species as modelled by i-Tree Eco.

Figure 7 Annual Carbon Sequestration Rate by Tree Species (i)

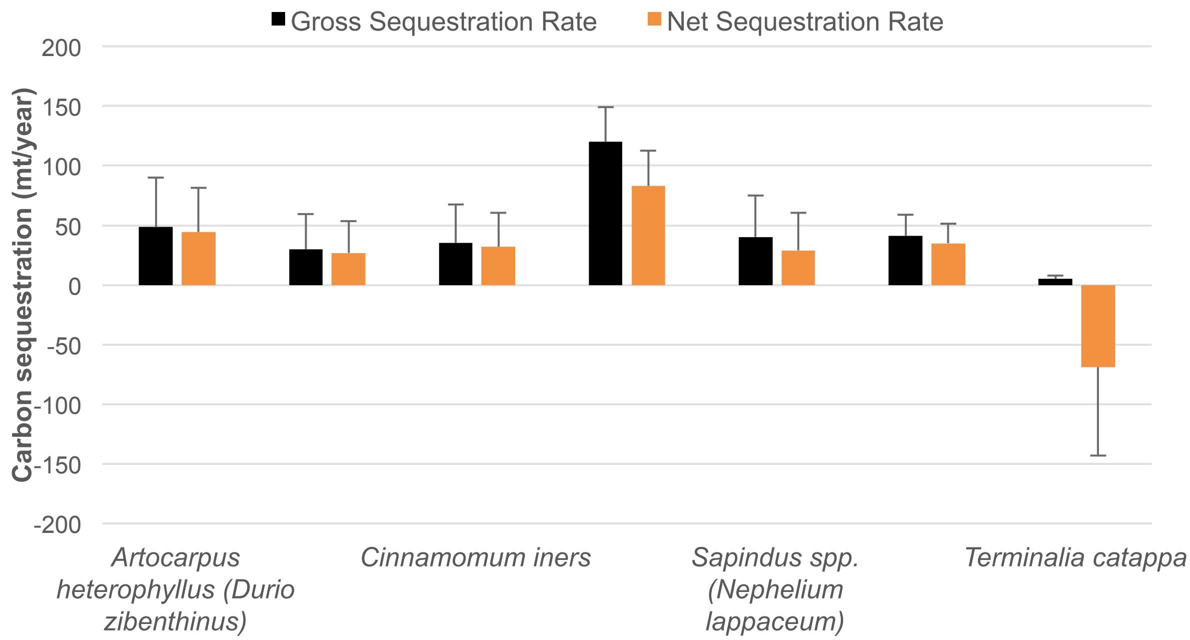
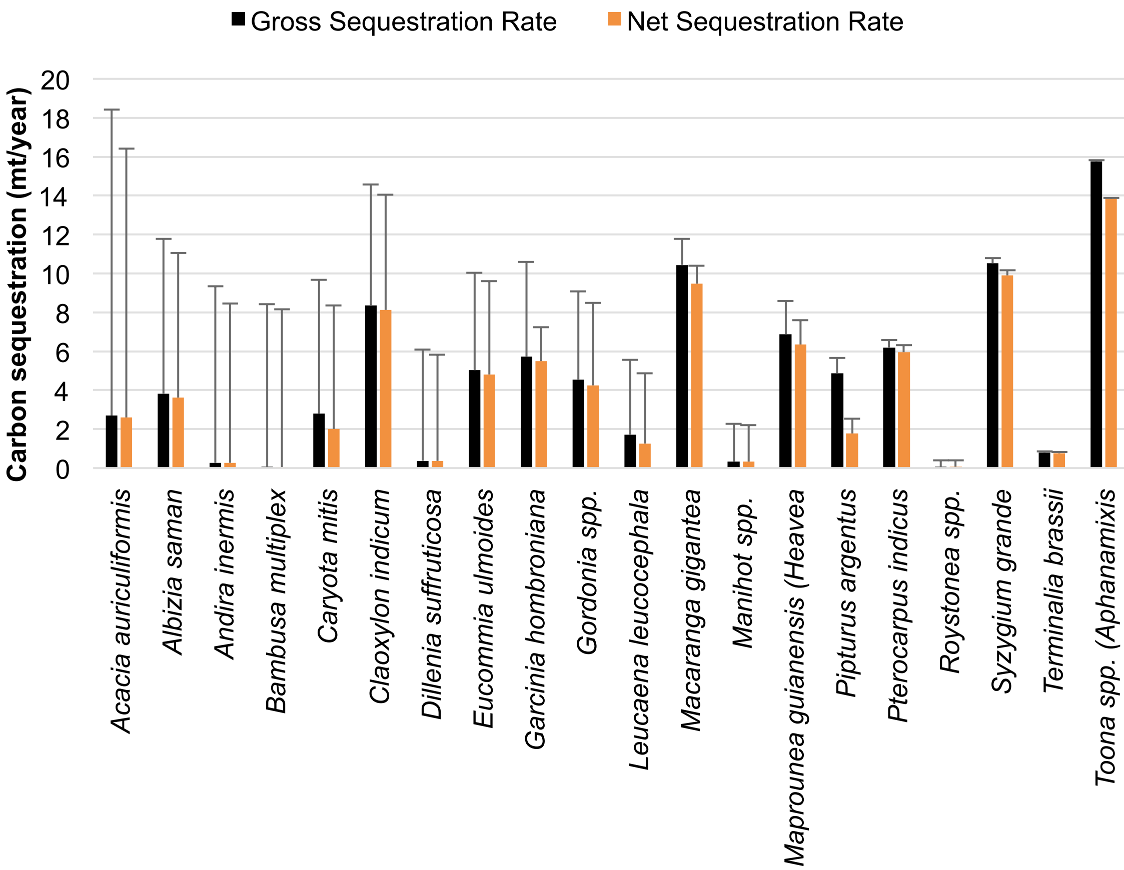
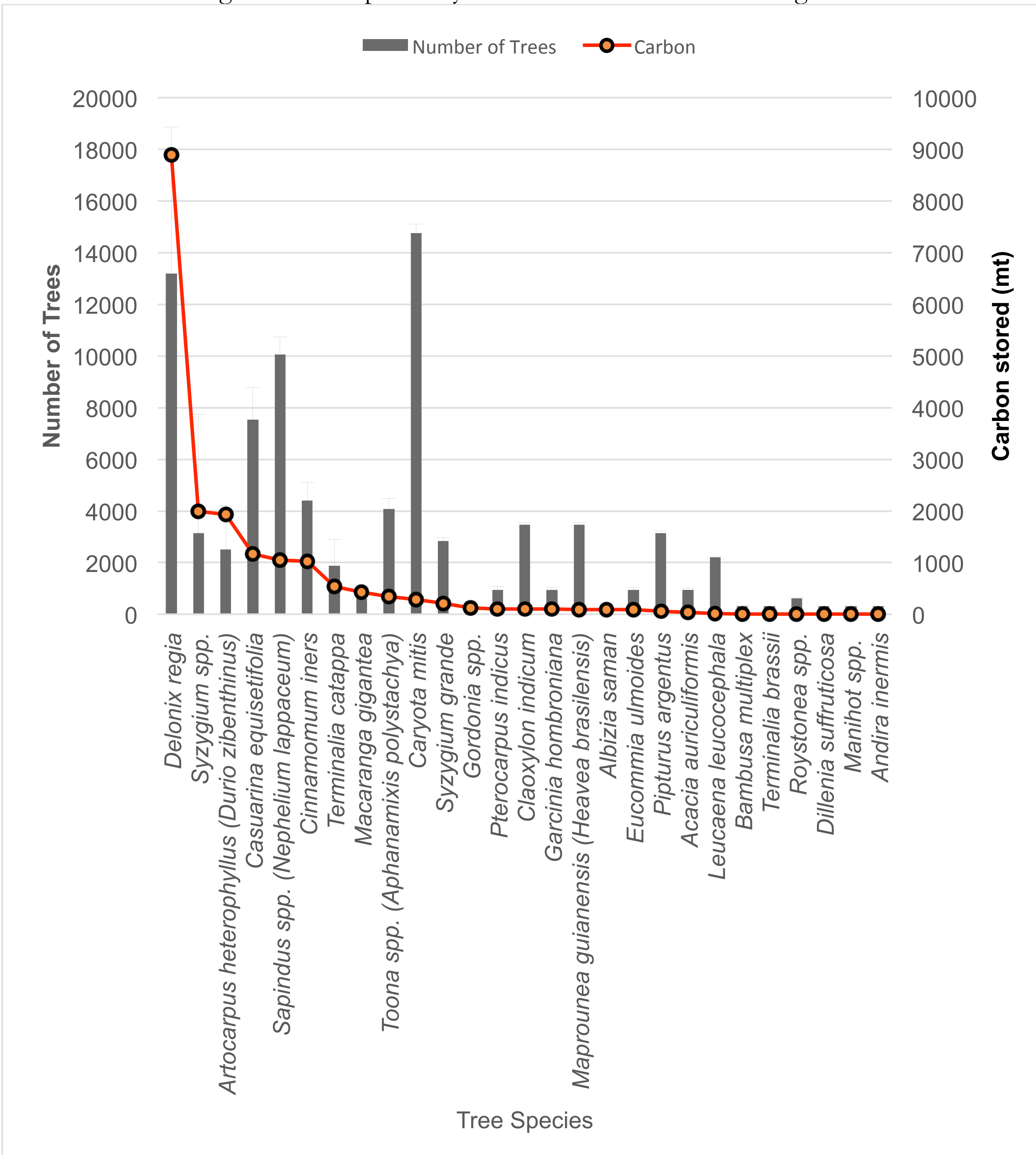


Figure 8 Annual Carbon Sequestration Rate by Tree Species (ii)



Notably, the dominant tree species by number of individuals does not store the greatest carbon content (Figure 9). The greatest amount of carbon is stored in the second most common species in Punggol Forest, *Delonix regia*, while the most common species *Caryota mitis*, ranks 10th out of the total of 27 species. This is possibly due to *Caroyta mitis*' higher green mass to solid dry mass proportion as a palm, compared to dipterocarp species such as *Delonix regia* and *Syzygium* spp. (Brown, 1997). *Caryota mitis* has a leaf biomass of 0.020594mt per individual, much higher than the all-species average leaf biomass of 0.017181mt per individual.

Figure 9 Tree Species by Abundance and Carbon Storage



Discussion

Baseline values on carbon ecosystem services

The modelled results from i-Tree Eco on Punggol Forest's structure, composition and carbon services are specific to this case study and thus must not be extrapolated to characterize deforestation in Singapore in other historical and spatial contexts.

Local-scale carbon stock assessments have been conducted for forests in cities (Jim and Chen, 2009) but are not comparable with this research for several reasons. Tree cover, density and forest maturity affect carbon sequestration and storage rates. Sequestration rates decrease as forests mature due to a higher proportion of dead trees and large diameter trees. Natural forest stands typically have higher tree cover than urban forests and thus store and sequester more carbon annually, but the reverse is true on a per unit tree basis due to higher growth rates as a result of lower tree density (Nowak and Crane, 2002).

The results of this study are baseline values necessary to quantify potential carbon services loss due to LULCC. Punggol Forest will be replaced with an urban matrix of street trees and parks as Punggol Eco-Town. While i-Tree Eco is unable to model future urban forestry composition and structure, its on-site vegetation assessment methodology is applicable to both urban and natural forest inventories. Thus, a longitudinal study of the same site after construction of Punggol Eco-Town is required to calculate a net carbon ecosystem services loss. These quantified baseline values provide an opportunity for urban forestry management policies to minimize this loss and thus retain some of the original carbon storage and sequestration values.

Urban forestry management

At present, urban forestry management in Singapore prioritizes shade and aesthetics for roadside greening (National Parkrs Board, 2015) and more recently, biodiversity (Khew, 2015). While climate cooling and biodiversity benefits are recognized, carbon ecosystem service benefits have been neglected.

i-Tree Eco results suggest a mismatch between planning priorities of biodiversity and carbon ecosystem services. Preserving the original biodiversity of Punggol Forest would not align with carbon services maximization. The importance value of each species found in Punggol Forest does not correspond to the carbon sequestration value per individual (Figure 10), nor the carbon stored per individual (Figure 11). However, the results of these figures cannot be taken at face value due to numerous factors that affect growth rate. To design the urban forest matrix in Punggol Eco-Town, identifying tree species with significant carbon benefits, in addition to biodiversity value, are required to minimize the loss of ecosystem services and maximize benefits of urban forestry.

Figure 10 Net Carbon Sequestration and Importance Value of Tree Species in Punggol Forest

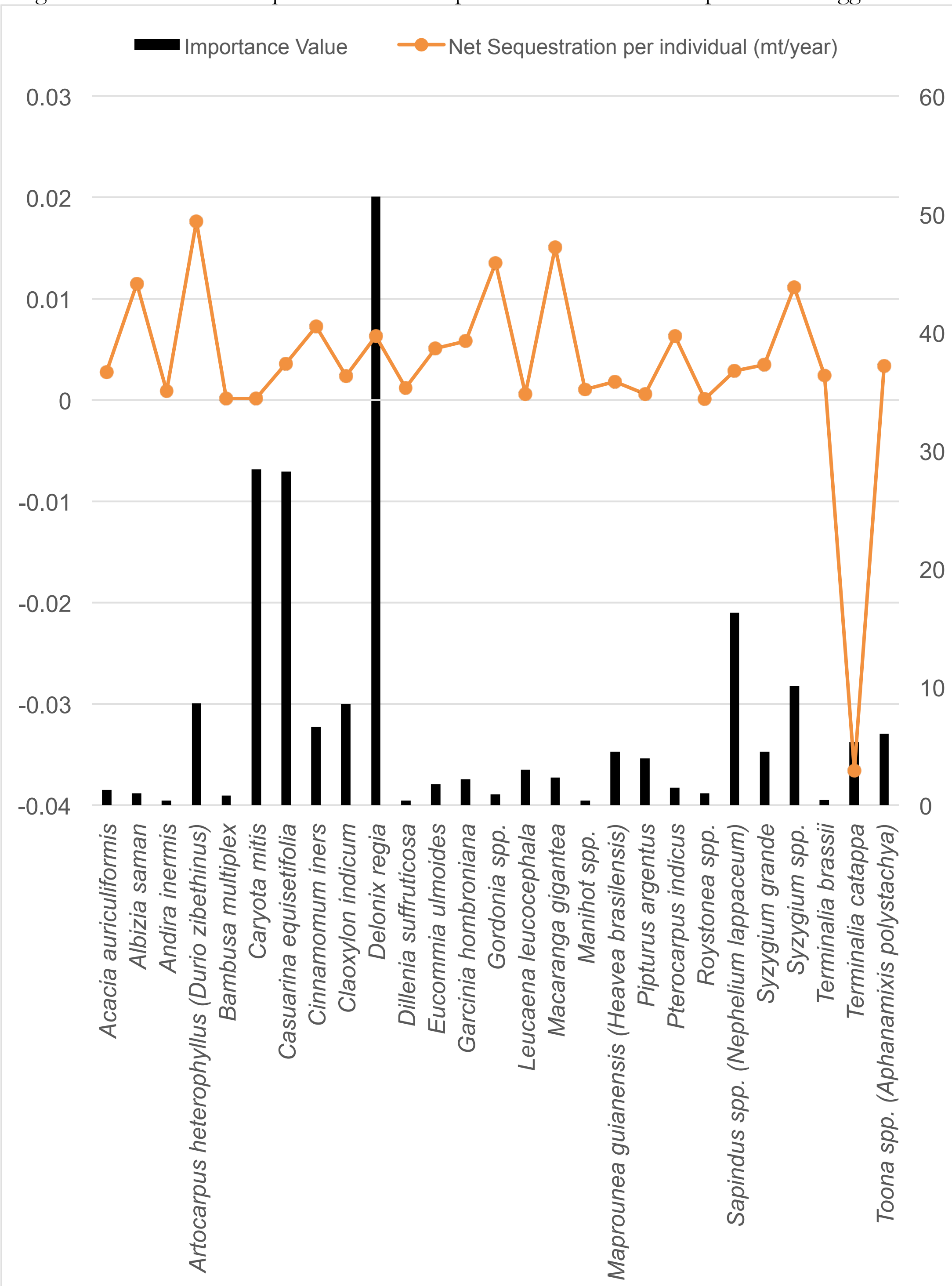
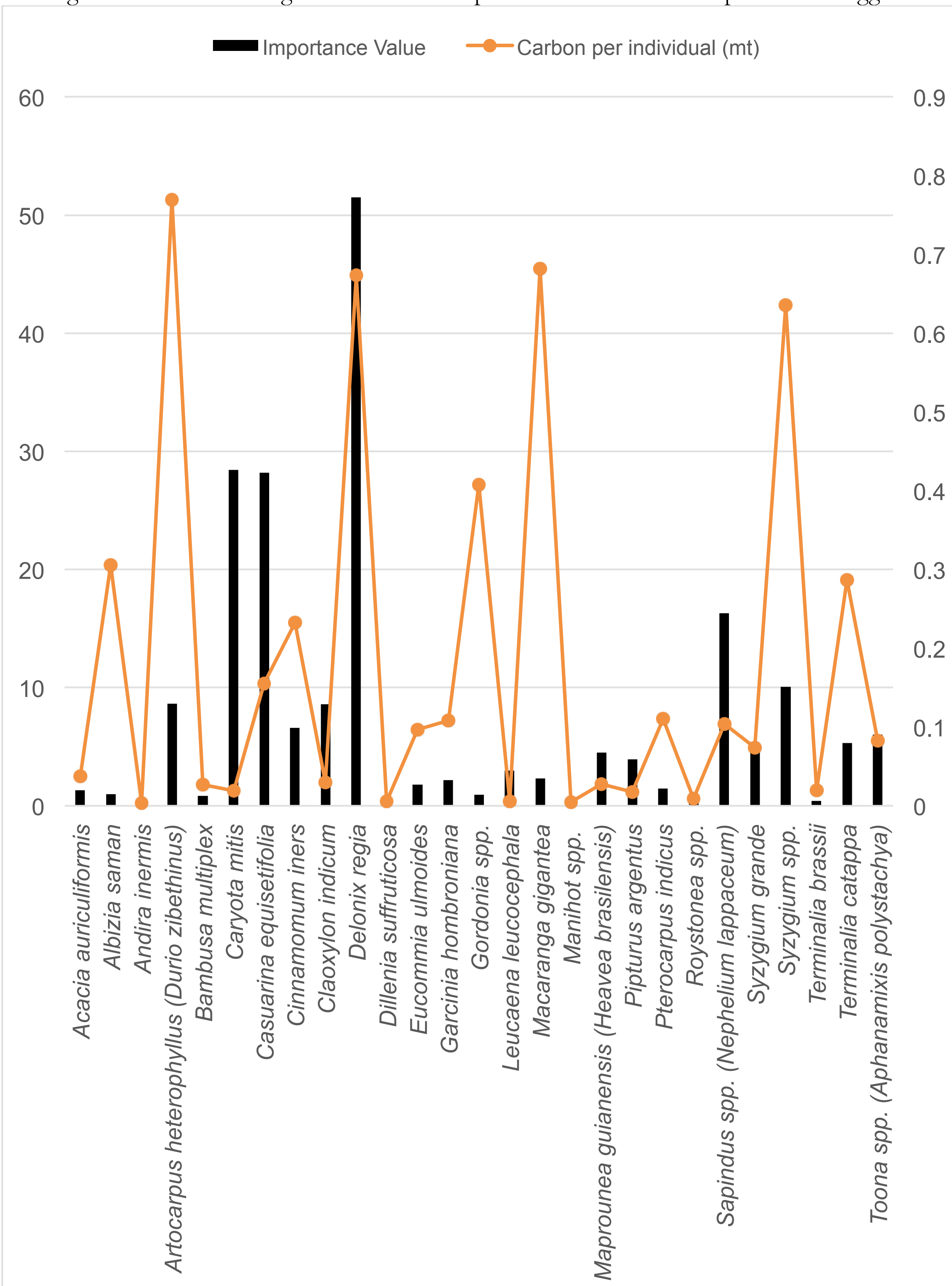


Figure 11 Carbon Storage Per Tree and Importance Value of Tree Species in Punggol Forest



Conclusion

This study used a modeling tool, i-Tree Eco, to quantify ecosystem services that affect the climate – carbon storage and sequestration. It uses a case study of planned LULCC in the form of deforestation and urbanization, and uses the local-scale study site as a baseline of carbon accounting. It finds a *potential* loss in carbon storage and sequestration services as Punggol Forest is deforested to make way for Punggol Eco-Town. Calculations using i-Tree Eco indicate that up to 1637kg/year/ha of annual carbon sequestration and 18708mt of carbon storage could be potentially lost.

Extrapolating these insights from the case of Punggol, several directions for informing climate ecosystem services management in planned cases of LULCC from forest to urban area can be considered. Prioritizing tree species for their carbon service value is proposed as a planning priority in urban forestry. Further studies to monetize the quantity of carbon storage and sequestration rate lost into a cost could be conducted, thereby allowing lost ecosystem services to support urban planning cost-benefit decision-making in the future. The hope is that these results can inform future local-scale sustainable urban design strategies, such as reforestation in tandem with urbanization through green infrastructure to restore the ecosystem services lost.

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Appendices

Appendix A:
List of Tree Species in Punggol Forest Identified from Vegetation Survey

NO.	SCIENTIFIC NAME	COMMON NAME OF SPECIES	SPECIES CODE IN I-TREE
1	Acacia auriculiformis	Acacia	ACAU2
2	Aphanamixis polystachya	Pithraj	Not Found
3	Bambusa multiplex	Bamboo	BA2
4	Caryota	Fishtail Palm	CA43
5	Casuarina equisetifolia	Casuarina	CAEQ
6	Cinnamomum iners	Cinnamon	CI4
7	Claoxylon indicum	Claoxylon indicum	CL2
8	Delonix regia	Flame of the Forest	DERE
9	Dillenia suffruticosa	Simpoh Air	DISU11
10	Durio zibethinus	Durian	Not Found
11	Garcinia hombroniana	Mangosteen	GAMA10
12	Gordonia singaporeana	Gordonia	GO7
13	Hevea brasiliensis	Rubber	Not Found
14	Leucaena leucocephala	Leucaena leucocephala	LELE
15	Macaranga gigantea	Giant Mahang	MA4
16	Manihot esculenta	Tapioca	MA27
17	Nephelium lappaceum	Rambutan	Not Found
18	Pipturus argenteus	Pipturus argenteus	PI17
19	Roystonea regia	Royal Palm	RO9
20	Syzygium glaucum	Syzygium glaucum	SY8
21	Syzygium grande	Sea Apple	SYGR2
22	Syzygium zeylanicum	Syzygium zeylanicum	SY8
23	Terminalia brassii	Brown Terminalia	TE4
24	Terminalia catappa	Indian Almond	TECA

Appendix B: Punggol Forest Tree Species Replacement Justification

CHARA-TERISTICS	ORIGINAL SPECIES	REPLACEMENT SPECIES
Tree 1	*Hevea brasilensis* (Rubber)	*Maprounea guianensis* (same family *Euphorbiaceae*)[1]
	 Source: Wikimedia Commons  Source: Southeastgrowers.com	 Source: Flickr  Source: Useful Tropical Plants
Leaf shape	· alternate leaves · separate leaflets · 3 leaflets per leaf stalk (trifoliate) · elliptical leaflets · palmately compound (radiate from single point at distal end of petiole)	· apically acute to mucronate to acuminate · abaxially often with basal glands
Leaf size	varying lengths of up to 45cm	
Tree shape	bole straight or tapered without buttresses	straight
Tree size	rarely exceeding 25m in height in plantations but wild trees of over 40m recorded	up to 25m tall
REPLACED SPECIES	➔ ***Maprounea* spp.**	
CHARA-	*ORIGINAL SPECIES*	*REPLACEMENT SPECIES*

[1] Esser, H.-J. 1999. Taxonomic notes on neotropical Maprounea Aublet (Euphorbiaceae). *Novon*, 32-35.

TERISTICS

Tree 2	*Durio zibenthinus* (Durian)[2]	*Artocarpus heterophyllus* (Jackfruit)[3]
	 Source: Anthropogen  Source: Blogspot Archives	 Source: Growables.org  Source: Flora Italiana
Leaf shape	· elliptic to oblong · apex acuminate · entire · alternate · petiolate	· elliptic to oblong · alternate · entire · glossy · simple leaves
Leaf size	10–18cm	up to 16cm
Tree shape	bole straight or tapered without buttresses	bole straight
Tree size	large, 25–50m	8–25m
REPLACED SPECIES IN i-TREE ECO	➔ ***Artocarpus heterophyllus***	

[2] Brown, M.J., 1997. *Durio, a bibliographic review*. Bioversity International.

[3] Prakash, O., Kumar, R., Mishra, A. and Gupta, R., 2009. Artocarpus heterophyllus (Jackfruit): an overview. *Pharmacognosy Reviews*, *3*(6), p.353.

CHARA-TERISTICS	ORIGINAL SPECIES	REPLACEMENT SPECIES
Tree 3	*Nephelium lappaceum* (Rambutan)[4]	*Sapindus* spp. (of the Lychee family *Spindaceae*)[5]
	 Source: Varashree Nursery  Source: USDA Agricultural Research Service	 Source: Anthropogen  Source: Blogspot Archives
Leaf shape	· pinnately compound · alternate · no end-leaflet	· pinnate · alternate · 14-30 leaflets · no end leaflet
Leaf size	10–18cm	15–40cm
Tree shape	open crown of large branches	straight
Tree size	10–12m	up to 25m
Selected Replacement	➔ ***Sapindus* spp.**	

[4] Arenas, M.G.H., Angel, D.N., Damian, M.T.M., Ortiz, D.T., Díaz, C.N. and Martinez, N.B., 2010. Characterization of rambutan (Nephelium lappaceum) fruits from outstanding mexican selections. *Revista Brasileira de Fruticultura*, *32*(4), pp.1098-1104.

[5] Brummitt, R. K. 1999. Report of the Committee for Spermatophyta: 48. (Taxon) 48:369-370.

CHARA-TERISTICS	ORIGINAL SPECIES	REPLACEMENT SPECIES
Tree 4	*Aphanamixis polystachya* (Pithraj)[6]	*Toona* spp. (same family *Meliaceae*)[7]
	 Source: NatureLoveYou.sg  Source: NatureLoveYou.sg	 Source: Forest & Kim Starr  Source: Green Clean Guide
Leaf shape	· pinnately compound · alternate · rachis pulvinate · 4–8 pairs of leaflets	· pinnate · 5–10 pairs of leaflets · no lobes or teeth on leaves
Leaf size	>30cm	50–70cm
Tree shape	10–12m, open crown of large branches	up to 25m
Tree size	up to 20m tall	up to 25m
Selected Replacement	➔ ***Toona*** **spp.**	

[6] World Conservation Monitoring Centre 1998. In: IUCN 2006. 2006 IUCN Red List of Threatened Species. Retrieved 12 December 2015.Aphanamixis polystachya.

[7] Brummitt, R. K. 1999. Report of the Committee for Spermatophyta: 48. (Taxon) 48:369-370.